Use of Plastic in Greenhouse Vegetable Production in the United States

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Summary. **The evolution of plastic uses (excluding glazing) in the production of greenhouse vegetables is presented. Plastics are used in almost every aspect of crop production, including providing a barrier to the soil, lining crop production troughs, holding soil and soilless media, and providing a nutrient film channel. Irrigation systems have become very elaborate, with various plastic products used to transport water and nutrients and to provide a means of emitting nutrient solution to the crop. The greenhouse environment is managed from several plastic components, including air distribution tubes, shade materials, and energy curtains. Plastics are now common in greenhouse vegetable crop training, insect monitoring, post-harvest handling, storage, and marketing.**

Vegetables have been produced in commercial greenhouses in the United States for more than a century. The total greenhouse vegetable area in 1899 was 42 ha, with 16 ha of that total in the Boston area (Galloway, 1899). The production area in the United States had increased to 520 ha by 1929, but declined to 230 ha in 1969 and to 195 ha in 1974 (Hickman, 1988). Production returned to 230 ha by 1978, but again declined to 120 ha in 1988. The most recent production estimate was 145 ha (Hickman, 1992).

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The areas of traditionally high production in the 1960s and 1970s included Cleveland and Toledo, Ohio; Grand Rapids, Mich.; Indianapolis; and Boston. Production in these areas has declined substantially due largely to high energy costs and a conversion of greenhouse space to production of bedding plants (Wittwer, 1971a, 1971b; Wittwer and Honma, 1979). In the late 1960s and early 1970s, greenhouse production began to increase in areas of the southwestern United States, where higher amounts of sunlight, lower humidity, and reduced labor costs were available compared to northern regions (Wittwer, 1971a). Recent surveys showed an increase in production in the southeastern United States, especially Florida (Hochmuth, 1990b). Florida has an estimated 30 ha in production followed by California at 20 ha. Tomato *(Lycopersicon esculentum)*, cucumber *(Cucumis sativus)*, and lettuce *(Lactuca sativa)* continue to be the leading greenhouse vegetables (Hickman, 1992).

Greenhousevegetables were all produced in soil in the early part of the century-the primary crops were tomato, cucumber, and lettuce (Dalrymple, 1973). Soil culture was still the predominant production system in the early 1970s (Stoner, 1971). An estimated 70% of greenhouse crops in 1974 were in soil culture, with 30% in one of several different soilless systems. By 1978, 60% of the production was in a soilless system (Hickman, 1992).

Persistent problems with soil-borne diseases, such as *Verticillium, Fusarium,* and bacterialwilts, as well as tobacco mosaicvirus, required soil sterilization each year. Chemical or steam sterilization have been and still are used in the United States. Other problems that occur with soil culture are variable soil types, inefficient water and fertilizer use, difficulty in controlling soil temperature, and high labor requirement to prepare soil for cropping (Bauerle, 1984; Cotter and Chaplin, 1967; Jensen, 1968; Resh, 1987; Sheldrake, 1975; Sheldrake et al., 1964; Stoner, 1971; Straver, 1987; Wittwer and Honma, 1979). These persistent problems with soil culture led to the development of soilless production systems. Plastics have been an essential part of the development of many of the current soilless systems for greenhouse vegetables.

Plastics in production systems

The first approach to solving soil-borne disease problems was a system that became known as trough culture. The system, developed in England, used a polyethylene sheet to serve as a lining in a trough into which sterilized soil was placed. The lining of polyethylene served as a barrier to the nonsterile soil of the greenhouse floor. The objective was to confine the crop's root system to a limited volume of soil that could be sterilized thoroughly each year at half the cost of traditional soil sterilization. Variable fumigation results were obtained depending on soil texture (Wall, 1977).

Research in Europe in the 1960s concentrated on two systems-a soilless variation of trough culture and ring culture. The first variation of the trough system was to replace sterilized soil with peat or other soilless media (Taylor and Flannery, 1975). In ring culture, a bottomless ring of plastic or roofing paper was filled with media and the plants were placed in the ring of media (Jensen, 1968; Sheldrake, 1975; Wittwer and Honma, 1979). The plastic lining provided a barrier between the plant roots and the soil and successfully prevented soil-borne diseases from reducing yields (Jensen, 1968; Sheldrake et al., 1964). The plastic lining of troughs was 0.10-mm-thick polyethylene or sometimes polyvinyl chloride sheets.

Straw bales were used successfully as a growing medium in the United States as well as Canada and Europe. The practice was developed first in western Europe. Cucumber was the most commonly grown crop in straw bales. Bales of wheat straw generally were laid end-to-end on a layer of polyethylene film. The bales of straw were wetted thoroughly prior to planting and the crop was fertilized and watered by microirrigation as the season progressed. Practices such as covering the bales with a white reflective polyethylene film were used to some benefit (Johnson et al., 1985; Loughton, 1975; Wittwer and Honma, 1979).

In the late 1960s, the soilless materials used most often were peatmoss and vermiculite, but both were expensive. One problem noted with organic materials such as peat was the physical compaction and breakdown of materials during the season. Work in Arizona led to the development of a production system that used sand as the growing medium (Jensen, 1971a). In sand culture, the entire floors of greenhouses or troughs were covered with two layers of 0.15 -mm-thick black polyethylene. A system of drain pipes in the bottom of the troughs or a graded bed facilitated movement of excess nutrient solution from the root zone of the crop. After a crop season was completed, the sand was covered with a polyethylene sheet (tarp) and fumigated by injecting a fumigant through the irrigation system. After fumigation, an overhead irrigation system was used to leach the remaining fumigant and salts from the sand.

The layer of polyethylene as a barrier to soil-related problems, such as disease organisms and nematodes, had proven very successful with the work in the 1960s. In the 1970s, continued research efforts all over the

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world used the concept of a plastic barrier and a soilless media to grow vegetables in a greenhouse. Many different types of containers to hold the media were tried. The most common containers in the United States, however, were polyethylene bags and rigid plastic pots (Johnson et al., 1985). Containerized soilless culture provided several advantages over soil culture and quickly became popular in many areas of the world, including the United States (Bauerle, 1984; Carpenter, 1985; Wittwer and Honma, 1979). Some of the most important advantages of a containerized culture such as bag culture were listed by Bauerle (1984) and included:

- Excellent media uniformity
- Promotion of early yields
- Reflection of light to crop by floor mulches
- Efficient irrigation water and nutrient use
- Reduction of disease with nonrecirculated solution
- Fast crop turn-around time
- Reduced labor compared to soil culture

"Groundwater contamination is an important concern to all in agriculture, including greenhouse producers."

Three bag types are in use today-layflat, upright, and vertical (a long, hanging or standing bag). The vertical bag system has not been used to any extent in the United States (Carpenter, 1985). Peat bags were used for the first time commercially in the United States in Cleveland, Ohio, in 1971 (Wittwer, 1971b). Layflat bags originated in Finland, where they were known as peat modules (Wittwer and Honma, 1979). Common bag sizes are 0.9 to 1.2 m long and 0.3 to 0.4 m wide. The most commonly used layflat bags contain 0.04 m^3 of a peat-lite medium and are designed for three tomato plants (Boodley and Sheldrake, 1977; Carpenter, 1985; Wall, 1977; Wittwer and Honma, 1979). A medium volume of 0.013 m^3 per plant is sufficient to produce maximum tomato yields (Snyder and Bauerle, 1985). The plastic bags for layflat bag culture consist of white, 0.10-mm-thick, ultraviolet (UV) -resistant polyethylene (Bauerle, 1984).

When bag culture is used with a soil floor, furrows are made in the soil to facilitate removal of excess nutrient solution from the double rows of bags. White polyethylene (0.10 mm) is used to cover the floor to provide a barrier between the soil and the bags and to reflect light to the crop (Bauerle, 1984; Johnson et al., 1985). Transplants grown in small, bottomless plastic pots are placed in holes cut in the tops of the layflat bags (Bauerle, 1984). Plastic trays facilitate handling potted transplants.

Upright polyethylene bags also are used for greenhouse vegetables. Many of the cultural practices are identical to those described for layflat bag culture. The most common bag size is 0.02 m^3, which will hold one cucumber plant or two tomato plants (Carpenter, 1981). Upright bags are purchased with pre-punched holes in the bottom for drainage and are filled with a soilless media at the greenhouse. Many soilless ingredients have been successful for upright bag culture. Often the media is a mixture of a peat, perlite, and composted or aged bark or wood shavings (Carpenter, 1985; Johnson et al., 1985). Upright bags have been filled with other soilless media, including vermiculite, styrofoam, sand, sawdust, rockwool, rice hulls, and peanut hulls (Bauerle, 1984; Carpenter, 1981, 1985; Johnson et al., 1985; Jones, 1983; Mauza, 1981; Sheldrake, 1980; Smith, 1987; Sweat and Hochmuth, 1991; Wilson, 1980; Wollard and Carlisi, 1986).

Rockwool, another soilless system, is so widely used in soilless culture that it deserves special mention. Rockwool is made by melting certain types of rock, most commonly basalt. The stream of molten rock is fed into a drum that rotates at high speed to spin the molten rock into fibers. Lime, a binder, and other additives are incorporated into the molten rock before it is spun. Rockwool for horticultural purposes is produced as a loose flock, or compressed into cubes or slabs. The loose flock can be mixed with other media for use in pots or bags. The cubes are used for propagation purposes and the larger slabs are wrapped in polyethylene for production of the crop (Smith, 1987).

Rockwool first was considered as a growing medium about 1970 in Denmark and now is being used around the world for greenhouse vegetables. Very little rockwool was used for crop production in the United States until the late 1980s (Carpenter, 1985). A transition to rockwool has gradually taken place in most greenhouse production areas in the United States.

Rockwool provides many of the same advantages over soil production as bag culture provides (Smith, 1987; Sweat and Hochmuth, 1991; Verwer, 1978). Plastics are again an integral part of the production system using rockwool. At present, most slabs used in the United States are 0.9 m long, 8 cm thick, and 15 to 20 cm wide. Each slab is wrapped in a white or white-on-black polyethylene sleeve. The medium-sized transplant blocks used in the transplanting stage also are wrapped on four sides with a polyethylene and paper sleeve (Sweat and Hochmuth, 1991). The transplant blocks can be laid out on a polyethylene sheet or placed in plastic trays during the growing stage before the blocks are moved to the slabs in the production house.

Most rockwool greenhouse layouts are similar to those described for bag culture. A layer of polypropylene cloth frequently is placed on the soil floor and covered by white polyethylene sheets for light reflectance (Hochmuth, 1990a). Some growers use a Styrofoam pad under the rockwool slab for some measure of insulation.

Groundwater contamination is an important concern to all in agriculture, including greenhouse producers (Biernbaum and Fonteno, 1989). Many of the newer rockwool production systems have improved methods to handle leachate so that it does not drain into the greenhouse soil year after year. Leachate collection systems in Florida consist of several plastic materials (plastic troughs and sheets) to aid in collecting the leachate from the slabs and channeling it out of the greenhouse operation for use in fertilizing pasture or other crops (Hochmuth, 1990a). Research has been conducted on recirculating the leachate from the rockwool system (Straver, 1988).

Nutrient film technique (NFT) was used first in Holland in 1961 and was later expanded to commercial production in England (Cooper, 1986). In NFT cropping systems, plants are supported in long, narrow waterproof channels, down which flows a very shallow stream of recirculating nutrient solution. The root mass develops in the channel, with the upper surface of the root mass exposed to air (Cooper, 1982). There were 1200 NFT operations in the United States in 1980, but failures reduced that number to 200 by 1984 (Carpenter, 1985). Major challenges with this system have included: undependable power supplies, resulting in power outages and lack of water in the channels; and disease organisms such as *Pythium, Phytophthora,* and *Fusarium* attacking the root system (Cooper, 1986; Sweat and Hochmuth, 1991; Verwer, 1978). Reported high yields have been a determining factor in growers being willing to take the risks with NFT (Cooper, 1982).

NFT culture has benefited greatly from plastics. The growing channels consist of a sheet of polyethylene supported by wooden or metal channels or platforms. Polyethylene provides the waterproof lining described by Cooper (Jones, 1983). A modern modification of the conventional polyethylene sheet channels is the extruded polyvinyl chloride (PVC) or polystyrene channel. Some growers have tried 10-cm PVC pipe as the channel, but this system appears to have increased disease risks due to lack of aeration of the root system (Sweat and Hochmuth, 1991). NFT lettuce is produced successfully in extruded PVC or polystyrene growing channels (Garnaud, 1985; Jones, 1983).

The NFT hydroponic system has other plastic components, including receiving basins of extruded PVC or a basin lined with polyethylene. Nutrient solution supply lines are generally PVC, and the small distribution connections between the supply line and the channels are polyethylene (Shippers, 1986). Reservoir tanks are lined with polyethylene or can be made entirely of polyethylene.

There have been reported cases of crops being damaged by toxic effects from some plasticizers used in plastic materials. Problems have been noted from some flexible PVC in NFT systems. Reconstituted flexible PVC is not recommended for use because of its mixed and unknown origin (Cooper, 1982; Garnaud, 1985).

Plastics in greenhouse irrigation

Irrigation technology is another aspect of greenhouse vegetable production that has benefited from plastics. Various types of plastics are used in the water conveyance and distribution systems, and plastics are usedwidely in the flow and pressure-control devices. Fertilizer often is applied with the irrigation water, and plastics are used in the nutrient metering pumps or proportioners and in the electronic control devices.

Plastic pipe has an interesting history, beginning with experiments by John Hyatt in the mid 1800s with cellulose nitrate (Garrett, 1975; Warp, 1971). During the decade before World War II, commercialization began for modern thermoplastics, including PVC andlow-density polyethylene (Garrett, 1975). PVC began replacing the metal pipes used to convey water to the greenhouses and to distribute water via sprinklers that were used previously in greenhouses. Plastic pipe came into favor due to its economy and ease of replacement (Chapin, 1969; Chapin and Chapin, 1971; Roth, 1971; Wieke, 1961). Plastics made it easier to incorporate specific tailor-made designs into irrigation systems such that "the sky became the limit" for plastics in agriculture (Smith, 1972).

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Although water conveyance switched over to plastic pipes, the basic methods of water distribution remained largely unchanged during the period between 1940 and 1960. Basic distribution systems included furrow, revolving sprinkler, and hand irrigation. Plastics started changing the scene for water distribution in the late 1960s, when drip irrigation commercialization began. Drip irrigation systems had their origins in the mid-1950s in Europe (Wittwer and Honma, 1979).

In the mid-1960s, experiments were begun with sewn plastic tubing, followed by "Drip Hose," which had flexible plastic leader tubes to place water at each plant (Chapin, 1971). The first test with drip tubing came in 1970, when Bernarr Hall tested "Twin Wall" tubing in California in 1970 (Chapin, 1971).

Drip tubing soon became commonplace

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in greenhouses largely due to its economy of installation and because a high degree of automation of irrigation was possible (Roberts and New, 1973; Spencer, 1973). Studies showed benefits-of drip irrigation including reduced amounts of water needed, fewer foliar diseases (compared to sprinkler), more-efficient use of labor (compared to hand-watering), and better yields (Kaniszewski and Dysko, 1988; Stoner, 1971). Automation with microirrigation sometimes permitted better yields and quality because several small daily irrigations were better than single irrigations for yield and quality, especially for small root volumes (Abbott et al., 1985; Snyder and Bauerle, 1985). Today, most operations growing vegetables in the greenhouse ground floor use some type of microirrigation system, including micro-emitter, drip, or ring-emitter systems.

Various microirrigation systems also are used in soilless vegetable culture, including peat bags, rockwool, perlite, and nutrient film technique. The most common system for peat bag, perlite, and rockwool involves black polyethylene laterals with small polyethylene "spaghetti" tubes transporting water to the plant (Chapin, 1969). Sometimes there might be one of several types of emitters, such as pressure-compensating emitters or emitters with sinuous pathways, used with the tubing. Otherwise, the delivery system involves only a short length of spaghetti tubing mounted on a plastic stake at the base of the plant. Flow rate is controlled by system pressure and size (inner diameter and length) of the spaghetti tube (Chapin, 1969).

Plastics also are involved in the control system for water delivery to the crop. Pumps have plastic parts, and, if fertilizer is applied, the proportioners and nutrient solution pumps can be largely of plastic components. Some proportioners can be entirely plastic except for a few metallic screws, a metallic spring, and rubber seals.

Pressure regulators, pressure gauges, ball valves, and solenoid valves often are largely plastic, especially for smaller systems. Plastic also is used in the electronic controllers, timers, and computers for the various components and housing units for these electronic devices.

Plastics in environmental control

Control of the greenhouse environment is essential for high yields of quality vegetables. Control of temperature, light, and humidity are each of special concern (Jones, 1991; Jarvis, 1992). Plastic is used in many of the components of greenhouse environmental control systems. Root-zone heating has been noted to be of importance, especially in northern climates (Roberts, 1985). Various designs of floor heating systems that use polyethylene, polybutylene, or PVC are described by Roberts and Mears (1984). These systems are used to distribute warm water from a boiler to heat the greenhouse floor area.

Unit space heaters, normally fueled with natural gas, liquid propane, or fuel oil, use fans to distribute heat within the greenhouse. Clear polyethylene tubes with prepunched holes along the tube are used in combination with this system to distribute carbon dioxide and heated or nonheated air uniformly in the greenhouse (Cotter and Seay, 1961; Duncan and Walker, 1979; Roberts, 1985; Roberts and Mears, 1984; Stoner, 1971). Many greenhouses come equipped with one large (60- to 90-cm-diamater) clear polyethylene tube running the length of the greenhouse about 3 to 4 m above the floor. Improved efficiency of heat distribution within the crop canopy can be obtained by using 12 to 30 cm of polyethylene distribution tubes placed on or near the greenhouse floor (Hochmuth, 1991). The use of polyethylene tubes to move air uniformly in the crop canopy has reduced relative humidity and moisture on plant surfaces, which has been important in reducing fungal diseases (Cotter and Seay, 1961; Killebrew, 1990).

The greenhouse energy curtain is another component of environmental control that involves plastics (polyethylene, polypropylene, or polyester). The curtains can serve two purposes-shading, or as a thermal screen for use in energy conservation. The thermal screen is deployed over the crop canopy at night to reduce heat losses by convection. Reduction in heat loss of 50% was shown in New Jersey by use of thermal screening (Roberts, 1985). A 40% to 45% reduction in heat loss has been shown by using thermal screens made of aluminized polyethylene and aluminized polyester laminated on clear polyethylene. One potential problem with thermal screens is an increase in the relative humidity in the crop area (Bailey, 1978; Stokes and Tinley, 1980). The increase in humidity under thermal screens has led to increased risk of tomato diseases such as gray mold *(Botrytis)* and leaf mold *(Cladosporium)* (Winespear and Bailey, 1978).

Curtains also are used for shading purposes inside the greenhouse above the crop area. Curtain materials most commonly used for these purposes include polypropylene, polyethylene, or a polyester-aluminum-polyethylene screening (Heacox, 1989; Meerse, 1987; Middendorp, 1987; Roberts, 1985; Snyder et al., 1991; Winespear and Bailey, 1978). Shade cloth material also is used commonly outside the greenhouse over the greenhouse glazing. This placement reduces radiant energy before it enters the greenhouse.

Durable cloth made of either black or white high-density polyethylene or polypropylene is used commonly in the United States.

Evaporative cooling systems are used in many greenhouses in the United States to moderate temperatures during warm periods. Two major types of evaporative cooling systems are used commercially today-wetted pad and high-pressure fog systems. In the 1970s, evaporative cooling pad materials commonly used included aspen pads, cellulose paper, cement-impregnated fibers, and rubberized hog hairs (Skinner and Buffington, 1977). Cellulose pads still are widely used; however, some newer types incorporate plastic fibers coated with an absorbent cellular foam. The plumbing for the cooling pad system consists of PVC pipe to carry water in a recirculating pattern from the polyethylene tank to the pad and back to the tank.

Plastic in crop management

The culture of greenhouse vegetables is labor-intensive. Changes in production practices often favor more-efficient use of time in production of the crop. Most greenhouse tomato varieties are indeterminate and are trained to a trellis system. The trellis support system consists of a cable stretched the length of the house anchored and supported by posts or the greenhouse structure itself. Individual tomato or cucumber plants are trained to a polypropylene or sisal string supported by the trellis cable (Boodley and Sheldrake, 1954; Hochmuth, 1991). The plant is supported on the twine by either wrapping the stem around the twine, attaching a plastic clip around the stem that anchors to the string, or by wrapping a plastic ribbon around the stem and string (tapener method) (Hochmuth, 1991). A single method or combination of these methods may be chosen by a grower.

Plastics in pest management

Insect pests can be a serious problem for greenhouse vegetable growers. Many pesticides once labeled for greenhouse vegetables are no longer available and alternative measures for pest control have become important (Heinz and Parrella, 1990; Hensinger, 1990; Kuack, 1989; Sase and Christianson, 1990). Screens placed over air-intake areas of the greenhouse have been shown to be effective in excluding certain insects from the greenhouse. Many of the screening materials being tested are. manufactured by the plastic film industry (Heinz and Parrella, 1990).

Another use of plastics in the management of insects in the greenhouse has been the use of sticky insect traps. Certain insect pests are monitored in greenhouses by the use of yellow or blue sticky traps because the insects are attracted to those colors (Aylsworth, 1990; Johnson, 1991). The traps range from plastic cards to polyethylene ribbons to which the sticky trapping material is applied.

Plastics in harvesting and handling

Plastics are benefiting the harvesting and packaging areas ofgreenhouse vegetable production andmarketing. In 1989, plastic packages were used in 17% of all food packaging. It is estimated plastic will represent 30% of all food packaging materials by the year 2000 (Fox, 1989). Plastics have contributed greatly to improving the vegetable industry's ability to deliver a high-quality product to the consumer.

Harvest containers made of high-density polyethylene have become common items in a grower's inventory. The smooth surfaces, light weight, structural integrity, and ease of handling and stacking have made these containers popular among greenhouse growers.

The long-fruited parthenocarpic cucumber commonly grown in greenhouses has a very thin and tender skin and is damaged easily by mechanical abrasion. To reduce moisture loss, field-grown cucumbers often are waxed as they go through a series of brushes and rollers, a process that would damage greenhouse cucumbers. Parthenocarpic cucumbers are wrapped in a thin sheet of polyethylene film commonly known as stretch wrap or shrink-wrap film (Holland, 1975; Jensen, 1971b; Schales, 1985). Cucumbers wrapped with a 0.03-mm-thick polyethylene film stored for 40 days at 11 to 13C can maintain marketability (Kubo et al., 1974). The greater the area of the cucumber exposed to air due to poor wrapping, the faster the cucumber breakdown in storage.

Postharvest handling of greenhouse lettuce also has been advanced with the use of plastics (Aharoni and Ben-Yehoshua, 1973). The leaf and semi-heading types oflettuce are grown more widely in greenhouses than crisphead types. Lettuce can be packaged in open-topped or perforated polyethylene bags. The bags then are placed in a shipping container, cooled, and shipped (Schales, 1985). Lettuce shipping boxes often are lined with polyethylene for bulk packaging of lettuce. New types of packages for hydroponically grown lettuce include lettuce crispers or "clam shells"-molded clear plastic containers that hold one head of bibb lettuce. The crisper is a two-piece container, a base and lid, especially used for supermarket sales.

Plastic products of all shapes, types, and sizes have become critical components in the production of vegetables in greenhouses. Many of these materials have led to innovative uses that revolutionized the way greenhouse culture was practiced throughout the

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world. This is likely to continue to be the trend in this highly technical and automated system of producing food.

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